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This research focused on developing of theoretical and algorithmic foundations for an applicable theory of cooperative mission control for teams of heterogeneous UAVs, motivated by the problem of coordination of activities in adaptive response to unknown events. The main results of the work include: (1) new techniques for the solution of adaptive search and sensor management, solving large scale combinatorial stochastic, dynamic optimization problems, based on integration of stochastic control and discrete optimization techniques; (2) distributed control techniques for trajectories of agents performing search and tracking while having to maintain communications connectivity; (3) cooperative control techniques for mission management involving rendezvouz problems of multiple agents performing tasks; (4) distributed algorithms for nonlinear resource allocation problems to agents; and (5) combinatorial algorithms for managing connectivity of air-to-air low directional communication networks. These results provide new models and algorithms for cooperative control that increase the level of autonomy that can be provided to UAVs, thereby enhancing the U. S. Air Force's capability to use unmanned vehicles without requiring large numbers of human operators.

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Distributed Mission Control for Unmanned Air Vehicles in Stochastic Environments

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Abstract

This research focused on the development developing of theoretical and algorithmic foundations for an applicable theory of cooperative mission control for groups of heterogeneous, distributed UAVs. The research is motivated by the problem of coordination of activities among UAVs in adaptive response to unknown events. The main results of the work include: (1) new techniques for the solution of adaptive search and sensor management, leading to solution of large scale combinatorial optimization problems in stochastic, dynamic environments, based on integration of stochastic control and discrete optimization techniques; (2) distributed control techniques for trajectories of agents performing search and tracking while having to maintain communications connectivity; (3) cooperative control techniques for mission management involving rendezvouz problems of multiple agents performing tasks; (4) distributed algorithms for nonlinear resource allocation problems to agents; and (5) combinatorial algorithms for managing connectivity of air-to-air low directional communication networks. These results provide new models and algorithms for cooperative control that increase the level of autonomy that can be provided to UAVs, thereby enhancing the U. S. Air Force's capability to use unmanned vehicles without requiring large numbers of human operators.

1. Introduction

In Joint Vision 2010, the Chairman of the Joint Chiefs of Staff outlined a vision of effective, efficient armed services for the next century. This document stressed the importance of ``information superiority" which he defined as ``The capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying and adversary's ability to do the same." The document identified the tactical use of autonomous assets as a key technology that will enable the commanders to obtain superior information, and conduct dominant maneuvers and precision engagements in an increasingly hostile environment. Information Superiority remains a key component of Joint Vision 2020 in order "to achieve decision superiority, to support advanced

command and control capabilities, and to reach the full potential of dominant maneuver, precision engagement, full dimensional protection, and focused logistics."

In recent years, the United States has been involved in military conflicts in Afghanistan and Iraq that saw increased use of remotely-piloted tactical aircraft such as Predators, Reapers and Global Hawks for surveillance and target prosecution. These vehicles enable the Air Force to accomplish missions that may be difficult for manned aircraft due to survivability or other reasons. These missions include Suppression of Enemy Air Defenses (SEAD), moving target attack, fixed target attack, Intelligence Surveillance and Reconnaissance (ISR), jamming, theater missile defense, and counter weapons of mass destruction. UAV prototypes have demonstrated so far the capability for unmanned flight.

One of the major limitations of current tactical unmanned air vehicles (UAVs) is the high level of human control required to operate a single vehicle. This places limits on the use of large numbers of autonomous assets acting in a coordinated manner. To achieve the full potential of unmanned tactical vehicles, many of the decisions made by human operators will be generated by an intelligent cooperative control system, that will be guided by objectives and constraints provided by human operators. This cooperative control will have to solve complex dynamic decision problems associated with mission planning and control, in an unstructured and uncertain environment, in near real time, and without human intervention, adapting in an intelligent fashion to events which arise in a hostile, uncertain and rapidly evolving environment. This requires new technology for *cooperative, distributed mission control*, capable of selecting and coordinating the activities of multiple heterogeneous platforms to achieve a common objective.

This report summarizes the results of our investigations towards the development of theoretical foundations for an *applicable theory* of cooperative, distributed mission control for teams of heterogeneous UAVs, based on the application of distributed optimization models and techniques. Our results focus on mathematical models that abstract classes of problems associated with missions conducted by unmanned air vehicles, and develop algorithms to compute optimal or near-optimal decisions for these models, guided by inputs from human operators concerning desirability of outcomes. These algorithms provided the foundations for increased automation in the operation of unmanned air vehicles, and will allow the U. S. Air Force to enhance significantly its capability to employ unmanned vehicles without relying on large numbers of human operators to control and coordinate the individual vehicles.

The rest of this report is organized as follows: The next section provides an overview of the principal results of this research. Section 3 summarizes the personnel supported under this grant. Section 4 contains the list of publications that document the results.

2. Principal Results

In this Section, we present the main results of our work. The work consisted of detailed exploration of different decision problems associated with cooperative control of teams of unmanned vehicles conducting missions in uncertain environments.

A. Distributed Control and Optimization in Energy Limited Cooperative Systems

Many modern optimization and control tasks can only be accomplished by deploying a distributed cooperative system, which consists of geographically distributed agents working on missions that require their combined efforts, with little or no central coordination. Our research focused on the problem of deploying and moving sensors to achieve coverage control in order to maximize the detection probability of random events, taking into account the discontinuities introduced by obstacles, the limited sensing field of view of the sensors, and limits imposed in maintaining communications connectivity to other sensors [13],[20],[22]. Our results developed a distributed gradient-based scheme that uses only local information available to each distributed agent about its location and its neighbors' locations. We also developed a modified problem formulation with a different objective function which provides a more balanced coverage of the mission space when necessary.

We extended the results above to missions that search for new events, while maintaining continuous collection of previously observed events, motivated by the application of detection and tracking vehicles [39],[42]. We process the information generated by event detections using Bayesian techniques, to estimate recursively the locations of potential events. Once a set of high occupancy probability locations are identified, we develop a joint optimization problem incorporating both coverage and data collection requirements as objectives, and solve these in a distributed manner. The results were demonstrated in a robotic test bed as well as in simulation [39].

As a related problem, we developed an event-driven communication scheme to solve the problem of how and when agents should communicate in order to make their information exchange more efficient and thus save energy. Specifically, we formulate the problem as an optimization problem where multiple agents must choose their individual decisions in order to optimize a common objective while communicating with each other to exchange updated information. We obtain conditions under which the optimization process converges with asynchronous communication of state information among agents. We apply this asynchronous (event-driven) approach to the coverage control problem and numerically show that it substantially reduces energy consumption while preserving the same performance as a synchronous algorithm [19],[31].

B. Cooperative Mission Control for Multi-UAV Rendez-vous Problems

We studied missions where UAVs must visit multiple targets and obtain rewards associated with each target with the added requirement that two or more UAVs must be present in the vicinity of each target in order to collect the associated reward. The mission

setting is stochastic with targets possibly appearing or disappearing in real time. We developed a Cooperative Receding Horizon (CRH) controller to maximize the total reward obtained in a finite mission time horizon. In this approach (based on some of our earlier work under this grant) we control the motion so as to maximize the expected rewards over a planning window without explicit target assignment [41]. In particular, the receding horizon controller computes the optimal headings of the UAVs at the end of each planning horizon, such that the total expected reward obtained by the team is maximized (assuming no target emerges on the way during the planning horizon.) This heading is then executed for a shorter action horizon, unless a new target is detected, in which case the optimization is performed again. If there is no new target, then the optimal headings will be recomputed at the end of the action horizon. Even though no explicit task assignment is performed, we were able to show that the proposed controller drives UAVs to targets. Hence, the trajectory generated by the controller is "stationary" in the sense that the vehicles converge to some targets even though the control decision is made in real time with no explicit assignment involved. This convergence result was formally established for 2 UAVs and a single target [41]. Furthermore, this controller integrates the problems of task assignment and trajectory generation, both in an uncertain environment. To evaluate the quality of our CRH algorithm as to the objective of reward collection maximization, we have compared it to an approximate upper bound on the maximal reward collected. Extensive simulations show that the reward collected based on the CRH algorithm is close to this approximate upper bound in all cases considered, while the mission completion time is longer. This is expected, since the CRH controller is designed to hedge against uncertainty by not following straight line paths to targets.

C. Cooperative Mission Control for Adaptive Sensor Management

In this work, we developed cooperative control algorithms for surveillance missions involving teams of heterogeneous UAVs with combinations of active (tracking and imaging radar, LADAR) and passive (electro-optical, infrared) sensors that can focus on individual objects with different modes. These problems were motivated by sensors such as Global Hawk, Predators and other UAVs working at different ranges as part of a layered surveillance network. The goal is to coordinate the allocation of the multiple sensor resources, ranging from trajectories to sensing activities, in order to achieve an accurate representation of the location and identity of objects in the scenario, while doing this in an adaptive manner that exploits previously collected information.

In one of our approaches, we formulated the problem for controlling a set of sensors with a finite number of sensing options and finite valued measurements that were tasked to locate and classify all objects in an area of interest, as accurately as possible with limited sensing resources. We formulated this problem as a Partially Observed Markov Decision Problem (POMDP), with a combinatorially large state space and action space [1-3]. Thus, its exact solution required excessive computation. We exploited statistical conditional independence assumptions of measurements to approximate the original optimization problem by a convex relaxation of this problem that provided a lower bound on the achievable performance [3,29]. We developed a class of algorithms techniques

that obtained optimal adaptive solutions to this lower bound, combining techniques from integer programming with stochastic dynamic programming algorithms for solution of POMDPs. Furthermore, we developed control algorithms from the solutions of this approximate problem using receding horizon controllers in a model-predictive approach [30]. The resulting controllers provide superior performance to alternative algorithms proposed in the literature and obtain solutions to large-scale POMDP problems several orders of magnitude faster than optimal approaches. Surprisingly, the performance of the receding horizon controllers is close to the predicted lower bound performance.

In our work, we also extended our initial formulation, which focused on stationary objects, to scenarios with moving objects. We used Hidden Markov Models (HMMs) for the evolution of objects, according to the dynamics of a birth-death process. Along the lines of our previous results, we developed a new lower bound on the performance of adaptive controllers in these scenarios, associated with a solution of a large POMDP problem, developed algorithms for computing solutions to this lower bound POMDP that combine integer programming with stochastic dynamic programming. These algorithms can be used as before in a receding horizon adaptive control for sensor allocation in the presence of moving objects.

We also consider an adaptive search problem using energy allocation where sensing actions are continuous-valued and the underlying measurement space is also continuous. We extended our previous hierarchical approach based on performance bounds to this problem and developed novel implementations of stochastic dynamic programming techniques to solve this problem. Our algorithms are nearly two orders of magnitude faster than previously proposed approaches and yield solutions of comparable quality [47].

Although the above algorithms are significantly faster than alternative optimization approaches using dynamic programming, they still involve on-line solution of POMDPs in a hierarchical manner, which can be a major limiting factor in terms of computation requirements. Another limitation was that the observations provided by sensors had to satisfy a conditional independence assumption as well as being finite-valued, which limited the applicability of the results. To address this shortcoming, we developed a new mathematical theory for adaptive sensor resource allocation that models sensors as providing observations of primitive features as opposed to object types. In this approach, objects are modeled as spatially related collections of features, characterized by object type and pose; sensors measure noisy projections of these features subject to degradation by noise, obscuration, missed detections and added background clutter. Using techniques based on random sets, we developed several approaches to predict the value of information that would be provided by potential measurements. A promising approach was based on a new information-theoretic performance bound where much of the computations can be pre-computed off-line, which bounds the probability of confusing one object type with another [46]. These bounds can be used as surrogate performance measures for adaptive resource allocation algorithms that can scale to large numbers of objects while maintaining real-time performance. Furthermore, these algorithms can be implemented in distributed fashion across multiple platforms, using the

theories of distributed assignment algorithms. In simulations, the resulting algorithms achieved performance comparable to on-line, adaptive sensor management algorithms with much reduced computation requirements.

D. Dynamic algorithms for topology selection and maintenance in airborne wireless communication networks

An important problem faced by air vehicles is that maintaining an air-to-air connected communication network can be challenging in hostile environments. This is due in part to the use of directional antennas (to increase anti-jam properties, and avoid hostile exploitation of communications) and to the rapid movement of air vehicles. The problem of choosing a network topology to connect communication nodes subject to specific objectives, constraints, and properties is a broadly studied problem, with approaches varying widely depending on the hardware capabilities and limitations, the required performance criteria, and the available budget. Our work was motivated by a topology problem in which naval, ground, air, and space vehicles require secure, high bandwidth data communications across long distances in an unstable environment. Each wireless connection in the network requires a pair of directional antennae; the connection is point-to-point line-of-sight, not broadcast over a wider region. While some nodes may be stationary, stable, and secure, the majority of the hundreds of nodes in the network are moving. As a result, a line-of-sight connection between a pair of nodes is subject to predictable and unpredictable interruption. Because the network is constantly evolving, new topologies must be generated very quickly so that network connectivity is maintained.

In this work, we developed combinatorial algorithms to solve the dynamic connectivity problem. We define this problem as finding a minimum degree-constrained spanning tree. We developed optimal integer programming algorithms that can generate the topology backbone for large point-to-point wireless networks quickly, even in networks with hundreds of nodes, by exploiting quick bounding strategies, and using a delayed row generation algorithm. We also extended this algorithm to variations of the topology problem, including scenarios where the antennae in the network consist of multiple incompatible technologies, and where the connectivity must be maintained over time with costs of switching links, in order to maximize connectivity over a time horizon. The resulting algorithms were compared with efficient alternatives discussed in the literature, and were shown to be significantly faster and more robust in finding optimal solutions. Our results provide algorithms for the design of real-time topology maintenance algorithms, as well as performance bounds for comparison with the performance of faster heuristic approaches for topology maintenance.

E. Distributed algorithms for nonlinear resource allocation

Nonlinear resource allocation problems are a class of optimization problems where heterogeneous resources that are geographically distributed have to be allocated to a diverse set of tasks, also distributed over a region of interest. The underlying

performance of executing a task is a nonlinear function of the bundle of resources assigned to it. These problems are motivated by diverse applications such as in search theory, weapon target assignment, sensor management, market equilibria, production planning, scheduling of mass screening tests and allocation of software-testing resources. The linear cost generalized assignment and transportation problems can be seen as special cases of these problems. These types of allocation problems arise in missions associated with unmanned vehicles. Our focus was in developing solution approaches for this problem that would be executed in a distributed manner by teams of unmanned air vehicles.

In this work, we developed a new class of algorithms for distributed nonlinear resource allocation based on nonlinear extensions of the auction algorithm for linear assignment problems, called RAP Auction [45]. This algorithm exploits the graph structure present in RAPs, plus integrating ideas from convex and combinatorial optimization. Unlike most previous techniques for this class of problems, it is applicable to arbitrary convex monotonic utilities, thus relaxing assumptions of differentiability and strict convexity. Furthermore, the algorithm has a simple computation structure that is amenable to parallelization.

We developed extensions of RAP auction and resource-wise optimization algorithms that are suitable for distributed computation, and established convergence of the algorithms to correct solutions under asynchronous, unreliable and delayed communications with minimal coordination capabilities. The RAP auction is a primal dual approximate technique with finite convergence, while the resource-wise optimization algorithm is an exact primal algorithm with asymptotic but geometric convergence. Using concepts from asynchronous optimization, we prove that the algorithms satisfy critical monotonicity properties that guarantee convergence to optimal solutions under totally asynchronous implementations.

3. Personnel Supported

The following personnel received support in part from this grant:

Professor David A. Castañón
Professor Christos G. Cassandras
Prof. Jianfeng Mao (PhD graduate 2009)
Dr. Darin Hitchings (PhD graduate 2010)
Dr. Karen Jenkins (PhD graduate 2010)
Dr. Thomas Vittolo (PhD graduate 2010)
Dr. Minyi Zhong (PhD graduate 2011)
Yanfeng Geng (PhD student)
Xuchao Lin (PhD student)

4. Honors/Awards

Prof. Castañón served as a member of the Air Force Scientific Advisory Board from October, 2006 to October 2010. Prof. Castañón served as the General Chair for the 2007 Conference on Decision and Control, and served as President Elect, President and Past President of the IEEE Control Systems Society in 2007, 2008 and 2009, respectively. He has been a member of IEEE's Society Review Committee since 2009.

Prof. Cassandras served as Editor-in-Chief of the IEEE Transactions on Automatic Control until 2009. He was elected a Fellow of the International Federation of Automatic Control in 2008. He served as Vice President for Publication Activities for the IEEE Control Systems Society in 2010, and is serving as President-Elect of IEEE Control Systems Society in 2011. He gave 6 Plenary/Keynote addresses at various international conferences over the period of this grant (2007-2010).

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